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FLATTENED MODE CYLINDRICAL AND RIBBON FIBERS AND AMPLIFIERS

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This application claims priority to U. S. Provisional Patent Application No. 60/475,550, titled "Flattened Mode Cylindrical And Ribbon Fibers And Amplifiers," filed June 3, 2003 and incorporated herein by reference.

The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to diffraction limited fiber lasers, and more specifically, it relates to fiber lasers characterized by almost constant electric field intensity over the entire core region of the fiber.

Description of Related Art

For applications requiring high beam quality radiation from efficient, compact and rugged sources, diffraction limited fiber lasers are ideal, and to date have been demonstrated at average CW power levels exceeding 100 W with near diffraction limited output and a narrow bandwidth light signal. For conventional single-core step-index single-mode fibers, this power level represents the scaling limit because of nonlinear and laser damage considerations. Higher average powers would exceed nonlinear process thresholds such as the Raman and stimulated Brillouin scattering limit, or else damage the fiber due to the high intensity level in the fiber's core. The obvious way to increase the average power capability of fibers is to increase the area of their core [1]. Simply expanding the core dimensions of the fiber allows a straightforward power scaling due to enhanced nonlinear and power handling characteristics that scale directly with the core area. Femtosecond, chirped-pulse, fiber lasers with pulse energies greater than 1mJ have been demonstrated in the literature [2] using this technique. This output energy was still limited by the onset of stimulated Raman scattering. However, the enhanced power handling

capability that obtains through this route comes at the expense of beam quality, as increasing the core diameter in standard step index fibers permits multiple transverse modes to lase simultaneously. Although this problem of multimode operation can be mitigated to some extent by appropriately designing the fiber's waveguide structure, limitations such as bend radius loss, sensitivity to thermally induced perturbations of the waveguide structure, and refractive index control, all become more stringent as the core diameter grows, limiting the extent to which the core diameter can be grown and still enabling single mode operation from the fiber.

The spatial mode character of the radiation supported by the fiber is of concern. Conventional single mode fibers have an electric field that falls of continuously as the radius increases. In the core, the electric field in conventional single mode fibers has a zero-order-Bessel-function-of-the-first-kind radial dependence, and outside the fiber core, a modified-Bessel-function-of-the-second-kind radial dependence. This means that in conventional fibers, the electric field intensity on the fiber axis is higher than in other parts of the core.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide fiber lasers characterized by almost constant electric field intensity over the entire core region of the fiber

This and other objects will be apparent based on the disclosure herein.

The present invention addresses the limitations described above and enables a new approach to single transverse mode operation of large mode area (LMA) fibers, providing a route to high average powers exceeding 1 kW from a single aperture in a Strehl-ratio-optimizing flat-topped output beam.

The approach described herein is radical in that it eliminates the single-mode fiber on-axis intensity peak through appropriately engineering both the refractive index profile and the gain profile to realize large mode area (LMA) fiber structures that, while supporting several transverse modes, only allow a preferred flat-topped mode to lase. This is due to the modal gain discrimination that is engineered in during the fabrication of the structure. These special flat-topped modes are characterized by almost constant electric field intensity over the entire core region of the fiber.

The present invention has applications in many areas. Some examples are:

Scaled power fiber lasers;

Laser defense applications;

Short pulse laser sources and amplifiers;

Front end pulse generation and amplification system for the National Ignition Facility (NIF) laser system at Lawrence Livermore National Laboratory;

Transport fiber and fiber laser sources for telecommunication applications;

Optical power distribution networks; and

Various materials processing and machining applications, including the following:

Metal cutting;

Metal brazing;

Deep penetration metal welding;

Plastic welding; and

Soldering.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A shows the radial refractive index profile of a 50 μm diameter cylindrically symmetric fiber according to an embodiment of the present invention.

Figure 1B shows the radial gain profile of the fiber of Figure 1A (0 indicates no gain and 1 indicates gain).

Figure 2 shows the only allowed m=0 eigenmode of the index modulated structure shown in Fig. 1A. Also indicated is the gain and the index profile (not to scale).

Figure 3A shows the only allowed m=1 eigenmode of the fiber structure shown in Fig. 1A. Also indicated is the gain profile and the index profile (not to scale).

Figure 3B shows the only allowed m=2 eigenmode of the fiber structure shown in Fig. 1A.

Figure 4 shows a one-dimensional flattened-mode structure that can be constructed from soft glasses and is compatible with refractive index control at the level of $1x10^{-3}$.

Figure 5 shows that the one-dimensional waveguide structure of Fig. 4 supports the flat-topped mode shown here. Also indicated is the gain profile and the index profile (but not to scale).

Figure 6 shows the calculated overlap of the eigenmodes of the one-dimensional waveguide shown in Fig. 4 with the gain-loaded portion of the waveguide, as a function of the eigenmodes' effective index value.

Figure 7 is an end on view of a ribbon fiber containing elevated index tabs in the strips located at the top and bottom of the waveguide region. These tabs enable the vertical transverse dimension of the waveguide to be increased

while still ensuring flat-topped mode operation in that dimension as detailed above.

Figure 8A shows the refractive index profile and preferred mode of a cylindrically symmetric LFM fiber.

Figure 8B shows a comparison of the intensity profiles of a step index fiber and a cylindrically symmetric LFM fiber with the same total power.

Figure 9A shows output energy vs. pump diode current for the step index control fiber and the LFM fiber.

Figure 9B shows Raman peak spectral power as a function of the pump diode current for the same fibers.

Figure 10 shows an embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention reduces the intensity of light propagating in the core by distributing it more evenly across the core area via careful design of the refractive index profile [3]. The primary issue that results from scaling the core is addressed. The enhanced power handling capability comes at the expense of beam quality, as increasing the core diameter in standard step index fibers permits multiple transverse modes to lase simultaneously. Although this problem of multimode operation can be mitigated to some extent by appropriately designing the fiber's waveguide structure, limitations such as bend

radius loss, sensitivity to thermally induced perturbations of the waveguide structure, and refractive index control, all become more stringent as the core diameter grows, limiting the extent to which the core diameter can be grown and still ensure single mode operation from the fiber. The large flattened mode fiber of the present invention addresses some of these limitations and enables a new approach to single transverse mode operation of large mode area (LMA) fibers, providing a route to high average powers exceeding 1 kW from a single aperture in a Strehl-ratio-optimizing flat-topped output beam.

There are two degrees of freedom in the way modal gain discrimination can be managed in cylindrically symmetric fibers. Both the refractive index profile and the gain profile can be modulated radially to first promote specific modal fields, and then to favor some subset of the total supported mode spectrum of the structure. As an example, Fig. 1A shows a specific refractive index profile and Fig. 1B shows a gain profile that together support a flattened-mode. A very low numerical aperture (NA) structure is utilized to limit the total number of modes that are guided by the fiber.

The particular design shown in figures 1A and 1B corresponds to a 50 μm diameter fiber core and uses refractive index values that are conveniently accessible in fused silica. The gain is confined to an interior region having a radial extent of 22.2 μm, leaving a 2.8 μm wide outer undoped annular ring with a refractive index elevated from the outer cladding by 5×10^{-4}. The specific choice

of the index structure shown in Fig. 1A limits the total number of supported transverse modes to only three, and as will be shown, one of these has the desired flat-topped irradiance profile. The gain profile shown in Fig. 1B is then designed to strongly favor this preferred flat-topped mode over the other supported modes. Importantly, the fiber design in Fig. 1A uses index step variations of 1×10^{-4}, which are within the control limits of today's fused silica based fiber preforms from which fibers are pulled.

Figure 2 shows the only allowed m=0 eigenmode **10**, where m refers to the azimuthal quantum number of the eigenmode ($e^{im\varphi}$), of the optical structure shown in Fig. 1A. Also indicated at **12** is the gain and at **14** the index profile (not to scale).

The elevated index in the annular ring between 22.8 μm and 25 μm is present to ensure the mode shown in Fig. 2 is confined. Additionally, the width and height of this elevated index ring is chosen to engineer the confined mode in Fig. 2 so as to have a nearly flat irradiance profile within the central portion of the fiber. Because a flat-topped profile is the aperture distribution that gives the highest Strehl ratio, this feature of the present fiber design is very important for any application requiring optimized on-axis laser intensity in the far field. Additionally, the flat-topped mode benefits damage considerations, as there are no local regions having peaked irradiance. The effective mean field diameter of the m=0 mode in Fig. 2 is 54 μm and was chosen to maintain robust single mode

behavior in the presence of the thermal gradients that will be set up in the actively pumped structure. This design consideration will be discussed in more detail below.

The gain experienced by different laser modes is proportional to the overlap factor, Γ, of the mode's intensity envelope with the gain-loaded portion of the fiber,

$$\Gamma = \frac{\int |E(r,\theta)|^2 g(r) r dr d\theta}{\int |E(r,\theta)|^2 r dr d\theta} \qquad (1)$$

where g(r) is a function with value unity in those portions of the fiber that are gain loaded and 0 where there is no gain loadingand where E(r, θ) is the electric field of the mode in for with the gain overlap is being calculated expressed in a cylindrical co-ordinate system across the cross section of the fiber and r and θ are the usual radial and azimuthal coordinates common in a cylindrical co-ordinate system. This is a straightforward calculation once the eigenmode fields are known. In addition to the m=0 eigenmode shown in Fig. 2, the optical structure shown in Fig. 1A also supports a single m=1 eigenmode **16** and a single m=2 eigenmode **22**, which are shown respectively in figures 3A and 3B. Figure 3A also shows gain **18** and index profile **20**. Figure 3B also shows gain **24** and index profile **26**.

The eigenmodes depicted in Figs. 2, 3A and 3B are the only allowed eigenmodes supported by the optical structure in Fig. 1A. The eigenmode shown if Fig. 2 fills the aperture and is nearly flat-topped in profile, which means it will have a high Strehl ratio, and for this reason is the desired mode to favor in the operation of the device. Locating the gain along the center of the fiber, coinciding with the index well there, as shown in Fig. 1A, gives a gain discrimination between the allowed modes that favors the flat-topped mode; the overlap of the flat-topped mode shown in Fig. 2 is 0.79, while that of the modes shown in Fig. 3A is only 0.58 for the m=1 mode and in Figure 3B is only 0.33 for the m=2 mode.

The same design rationale that went into engineering a cylindrical index profile to ensure it supported a flat-topped mode can also be applied to ribbon structures in the transverse dimension perpendicular to the ribbon-guiding dimension. An example of such a flat-topped enabling one transverse dimension index structure is shown in Fig. 4.

The connection with the two-dimensional cylindrically symmetric fiber shown in Fig. 1 is evident. The elevated index tabs at the edge of the waveguide region are engineered in their height and width to specifically support the flat-topped mode that is depicted in Fig. 5. Figure 5 shows the eigenmode **50**, the index profile **52**, and the gain **54**.

The graph in Fig. 6 plots the calculated overlap of the eigenmodes supported by the one-dimensional waveguide structure of Fig. 4, the gain-loaded portion of the waveguide, the Γ factor given by equation 1 above, as a function of the eigenmodes' effective index value. This is a straightforward calculation once the eigenmode fields are known. The effective index values, n_{eff}, associated with the various eigenmodes of the structure is defined by,

$$\beta = \frac{n_{eff}\omega}{c}, \qquad (2)$$

where β is the longitudinal wavevector associated with the eigenmode, ω is the radial frequency of the light propagating in the fiber core and c is the speed of light in vacuum. From equation 2 above it is seen that c/n_{eff} is just the phase velocity associated with the eigenmode as it propagates in the ribbon structure. The two parameters, n_{eff} and Γ, completely define an eigenmode in terms of its wave-optics propagation and energetics behavior. The spectrum of values of n_{eff} and Γ for a given structure completely defines its modal properties, which can be conveniently summarized in a plot such as Fig. 6. Examining Fig. 6, the highest effective index eigenmode, which corresponds to the flat-topped mode plotted in Fig. 5, is also the mode with the highest gain overlap. The larger number of eigenmodes supported by the one-dimensional structure of Fig. 4 compared to the cylindrically symmetric fiber structure of Fig. 1 is a result of the larger Δn (index variations) used in its design. Even so, the highest gain mode in Fig. 6 has

an overlap with the gain region that is discriminated by 5% from the next highest gain mode, a level that should be sufficient to measure experimentally. Figure 7 illustrates how this approach is applicable to the thin dimension of a ribbon fiber **70**, and shows elevated index tabs **72** and waveguide region **74**.

Figure 8A shows experimentally obtained refractive index profile **80** for the flat-topped fiber mode **82**. Figure 8B shows the intensity distribution of a large flattened mode fiber design (LFM) **84** and a control standard step index profile fiber **86** of the same core diameter normalized such that the total power contained in the two modes is the same. (i.e., The two intensity distributions contain the same total power after the integration over the full cross sectional area is performed.) The LFM design decreases the peak intensity on axis by a factor of 2.46, which should lead to a significant decrease in the amount of stimulated Raman scattering for a given pulse energy, while not compromising the power handling capability.

In one test, the inventors purchased a 30 μm core, 0.06 NA, step-index, control fiber (Nufern) with a 400 μm hexagonal cladding with a low index polymer coating (pump clad NA=0.37). The core was doped with Yb^{3+} such that there was an effective core absorption of 120 dB/m at 977 nm. Also purchased was a nearly identical fiber from Nufern, but with the raised ring that gives the LFM fiber its distinctive index profile. The inner core diameter of the LFM was 25.3 μm and the ~~outer core diameter was about 30 μm FWHM, the effective NA~~

of the structure was approximately 0.06. The outer cladding and Yb^{3+} doping were the same as for the control fiber.

The present inventors then coupled 1.2 ns, 1075 nm, 10 Hz stretched mode-locked laser pulses into 9.1 m of the control fiber and 8.3 m of the LFM fiber. The input energy coupled into the fiber cores was 15 μJ. Pump light at 977 nm from a 10W diode laser array was counter propagated through the fiber to pump the Yb^{3+} ions. The diode light was pulsed at 10 Hz for 1 ms timed to precede the arrival of the signal light. Figure 9A shows the amplified output energy of the control fiber **90** and the LFM fiber **92** as measured with a Molectron energy meter. As expected, they produce roughly the same output energy as a function of pump diode current. Figure 9B, however, plots the percentage of the signal power contained in the first stokes spectra of the fibers of Figure 9A as measured with an Ocean Optics fiber coupled spectrometer. The LFM fiber shows significantly less Raman energy build up as a function of diode current than the control fiber. This is in agreement with what was expected from the design. In addition, greater than 0.6 mJ output pulses were achieved from the LFM amplifier with less than 5% of the energy in the Raman spectral band by utilizing pulses stretched to 3 ns. With straightforward scaling of Yb^{3+} doping concentration to reduce the amplifier length, increasing the core size to 50 μm and increasing the pump energy, an optimized design could yield output pulses

with greater than 10 mJ of energy and virtually no degradation due to stimulated Raman scattering.

For present invention fibers with similar core sizes, doping concentrations and lengths, the present inventors have shown a significant decrease in the amount of Raman scattering in the LFM fiber over a standard step-index fiber. The inventors believe these fibers can be scaled to output energy in excess of 10 mJ in a straightforward fashion as shown in the table below.

Pulse energy (mJ)	Pulse length (ns)	Core size (μm)	Fiber length (m)	Fiber gain (dB)	Comments
1.2	0.4	50	2.6	26	Galvanauskas, et al. [1]
0.6	3	30	8.3	8	LFM result from this report Higher gains yield increase output energy before the onset of Raman scattering. Our result was hurt by low gain.
9	3	50	2.6	26	Estimated (assumes one overcomes Raman scatterin using Galvanauskas system and increasing pulse stretcl

					to 3ns)
21.6	3	50	2.6	26	Estimated from above base on using LFM design to further increase the Raman scattering threshold

In a high power optical fiber amplifier embodiment, the invention can be used to amplify either pulsed laser light or laser light that more closely approximates a continuous wave laser signal. A schematic of the amplifier is shown in Figure 10.

An embodiment of the optical fiber amplifier shown in Figure 10 consists of a signal input **100** consisting of a 1053 nm light source, which may consist either of chirped pulses from a 1053 nm mode-locked laser or continuous wave light from, e.g., a 1053 nm DFB laser. The signal light is focused through the first focusing lens **102**, whose focal length is chosen to optimize the coupling of the signal light to the large flattened mode of the LFM fiber waveguide **104** core. The LFM fiber **104** consists of a core with the waveguide and gain profiles shown in figures 1A and 1B, which support a large flattened mode at 1053 nm. The raise ring shown in Figure 1A is fused silica doped with a standard co-dopant (for raising the index of the fiber such) as germania, phosphorous or alumina. The center region is fused silica doped with Yb^{3+}, co-doped with aluminum and other dopants as needed to adjust the refractive index

appropriately. The Yb^{3+} concentration is such that 976 nm light propagating in the waveguide experiences a small signal absorption of greater than 120 dB/m. The fused silica outer cladding is hexagonal in shape with 400 μm between flats of the hexagon. Polymer outer coating on the fiber is a low index fluorinated acrylate creating a multimode pump light waveguide in the 400 mm cladding with an numerical aperture greater than 0.35. The fiber is 10 m long and wound around a cylindrical mandrel with a radius of about 4 cm, which is chosen such that signal light propagating in the large flattened mode experiences minimal bend induced attenuation, but signal light propagating in the higher order waveguide modes experiences significant bend induced attenuation. Variations in the manufacture of the fiber against the preferred ideal may alter this preferred radius, which may need to be determined experimentally for each lot of optical fiber. The particular fiber used in this reduction to practice was manufactured by Nufern to custom specifications. In order to suppress undesirable back reflections from the fiber endfaces into the amplifier, these end faces are preferentially angle cleaved or polished in a plane whose normal is 8 degrees off the cylindrical axis of the fiber. The signal light is amplified in the fiber and exits the opposite end, where it is collimated by a second lens **106** and reflected from a dichroic mirror **108** that has a high reflectivity at 1053 nm and high transmission at 976 nm. A high power pump diode **108,** such as a 976 nm LIMO 25 W fiber coupled laser diode with a spot size of 400 mm and an NA of

0.22, is imaged through a lens **110**, traverses the dichoric mirror and is imaged through the output collimation lens for the signal into the pump cladding of the fiber. Light from the pump laser is absorbed by the Yb^{3+} ions and provides the energy for the amplification of the signal light.

One skilled in the art can see that there are many variations on this amplifier that can easily be made without changing the basic design. These include varying the rare earth ion, pump laser and signal wavelength to achieve an amplifier in other wavelength bands. These also include deliberately providing feedback to the amplifier in place of a signal input in order to create a laser oscillator said feedback may be Q-switched or employ a saturable absorber to generate pulsed laser light as well as continuous wave laser oscillation. Such a laser could be frequency doubled or frequency mixed with a second similar laser to achieve a source of light at shorter wavelengths. This shorter wavelength light source could then be used as a pump laser source for other lasers or for optical parametric oscillators or amplifiers.

Further, an integrated chirped pulse amplifier could be made based on Figure 10 by adding a pulse stretcher at the signal input. One skilled in the art can also recognize that the optical amplifier may be altered to include a second pump laser at the fiber input, to be pumped only at the fiber input, may include one or more optical isolators to prevent feedback into the amplifier from optical components in other parts of a bigger system, etc.

References:

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3. A. K. Ghatak, I. C. Goyal, R. Jindal, "Design of waveguide refractive index profile to obtain flat modal field" SPIE Proceedings vol. 3666, pp. 40 (1998).

The above references are incorporated by reference.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The embodiments disclosed were meant only to explain the principles of the invention and its practical application to thereby enable others skilled in the art to best use the invention in various embodiments and with various modifications suited to the particular use contemplated. The scope of the invention is to be defined by the following claims.